PowerFactory model for multi-terminal HVDC network with DC voltage droop control

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Contents

1. Introduction

Nowadays, most of the installed HVDC systems are based on line commutated converters (LCC), since this technology offers a series of advantages, mainly low costs and losses. However, voltage source converters (VSCs) have recently drawn more and more attention, due to their high controllability. Moreover, recent developments have improved efficiency and power quality. For multi-terminal HVDC grids, the advantages of VSCs become so large, that VSC-HVDC systems are the only viable solution. Nevertheless, no VSC-based multi-terminal HVDC grids exist to date. This is the reason for which many research projects have recently focused on this topic.

The aim of this report is the development of a DIgSILENT PowerFactory model of a multi-terminal VSC-based HVDC network. The model of each terminal represents the VSC-HVDC converter with its control system and the corresponding measurement equipment. After a brief description of the models, a series of events are simulated, in order to test the performance of the controllers. At the end of the document, recommendations for implementation of additional structures in future work are provided, as well as a list of references to provide the theoretical background of the control features of the system.

2. Model description

2.1. Grid layout

The chosen grid layout is a multi-terminal HVDC (MTHVDC) network, which comprises three terminals. This is the basic configuration, which can be easily expanded at will, by simply applying the developed model in different layouts. The mixed AC/DC grid is illustrated in Appendix. It consists of two external AC systems feeding three AC busbars. Three VSCs connect these AC buses with three DC busbars, which are connected in a radial topology to form a multi-terminal HVDC network. The DC voltage level is 500kV; the AC RMS voltage is 400kV. Other levels of voltage can be applied with the implementation of suitably designed transformers. In this work, the DC voltage is selected to be always higher than the peak AC voltage, even in cases of AC overvoltage and/or heavy loading of the DC grid. In this way, the overmodulation of converters is avoided. The DC lines are represented by standard models and the DC cables are modelled according to reasonable assumptions.

2.2 PWM converter

In this work, the standard PowerFactory model of the two-level converter is used. The model does not include the switching pattern and simply derives the AC voltage value from the DC voltage and the modulation indexes. However, the level of detail is found to be suitable for RMS simulations. A more detailed type is available in the library of PowerFactory for EMT simulations.

2.3. Converter control system

The control strategies and consequently the structure of the control system highly depends on the grid layout and the terminals configuration. Usually, in a point-to-point topology, the converter in one terminal (usually the rectifier) performs the control of active power, while the converter in the other terminal controls the DC voltage. However, when expanding the DC grid to more than two terminals, this simple control strategy is found to be not sufficient for the safe and effective operation of the system. Therefore, a new strategy for controlling active power and DC voltage should be implemented. The method of DC voltage droop control has recently drawn the attention of researchers, who focus on establishing its operational principles and investigating its static and dynamic behaviour. This technique resembles the frequency droop control in AC systems.

In this work, the control system of the converter is suitably structured to host the DC voltage droop control block and other control features. The main control system is represented by a power control block, which is fed in a cascaded manner by more blocks performing different control actions. A DC voltage droop controller and a frequency droop controller act in parallel to set the active power reference. This reference value determines then the d-axis current set-point in the power controller. In a similar way, an AC voltage droop controller modulates the reactive power reference, which is then transformed into the q-axis current set-point. The fast current controller is represented by an integrated PI-controller, provided by the library of PowerFactory. The composite frame of the whole control structure is given in Figure 1.

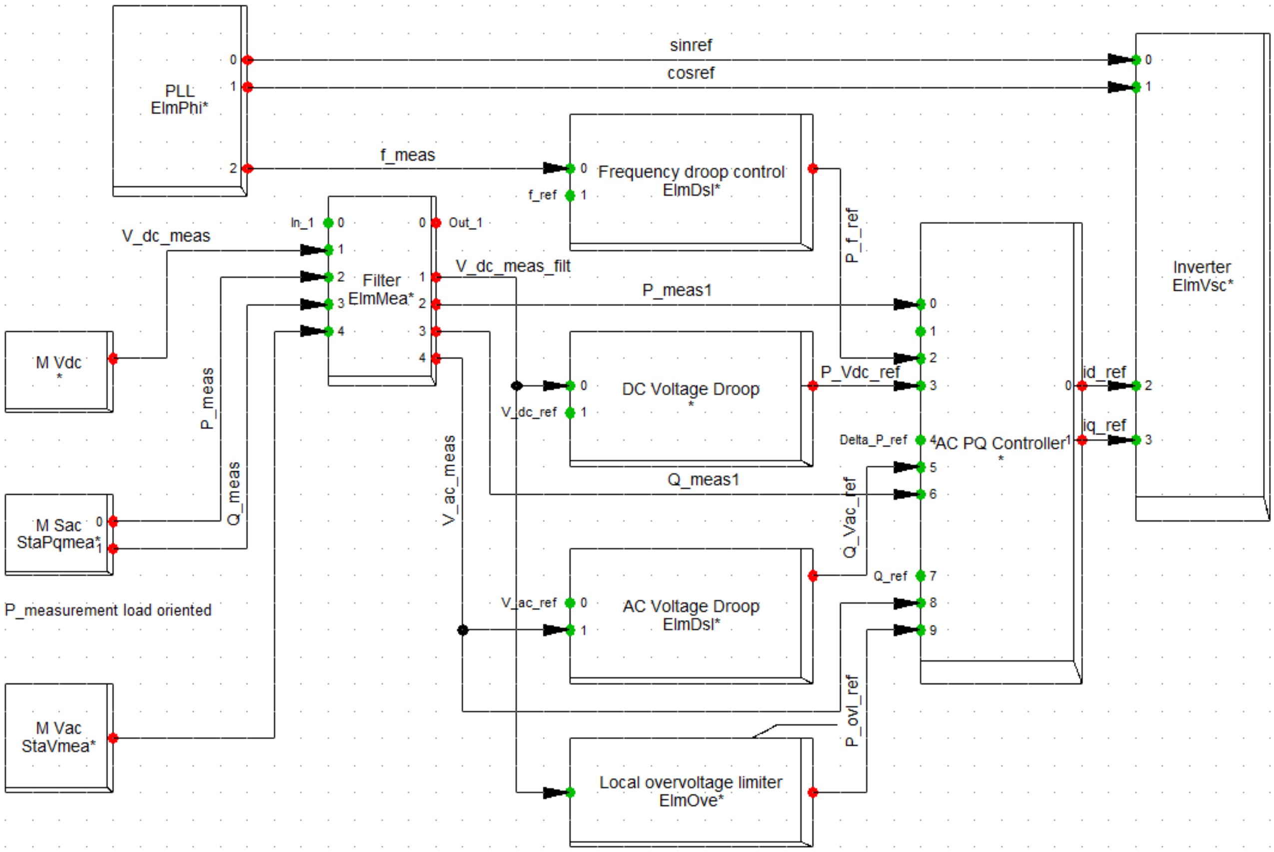

Figure 1 Converter control system

2.3.1. Power controller

The power controller realises a summation of the reference values coming from the control blocks upstream and adaptation of this signal to the current AC voltage level. In this way, the d- and q-axis current references are obtained, which control the active and reactive power, respectively. The structure of the power controller is depicted in Figure 2. The power reference signal P_{ref} is derived from initialisation, in order to avoid initial contribution from the DC voltage droop controller. For correctly initialising the model, the measured power P_{meas} is required as input, which is then fed into a sink block.

2.3.2. DC voltage droop controller

The DC voltage droop controller performs a proportional control action on the error between the reference DC voltage and its actual value. A gain R_{Vdc} determines the stiffness of the active power-DC voltage characteristic of the controller, in analogy with the frequency-active power characteristic of the frequency droop control technique in the AC systems. The diagram of the DC voltage droop controller is illustrated in Figure 3.

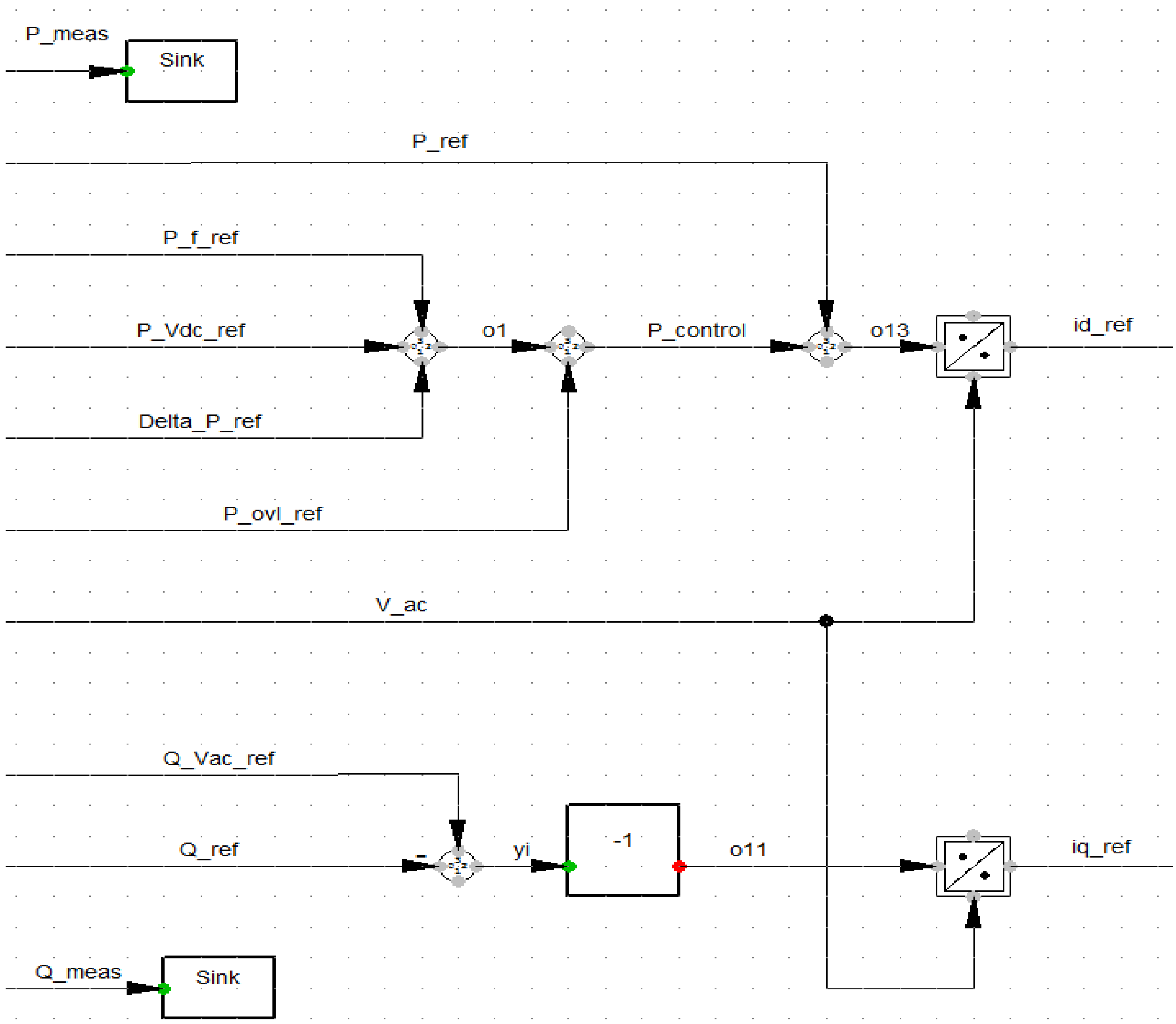

Figure 2 Power controller

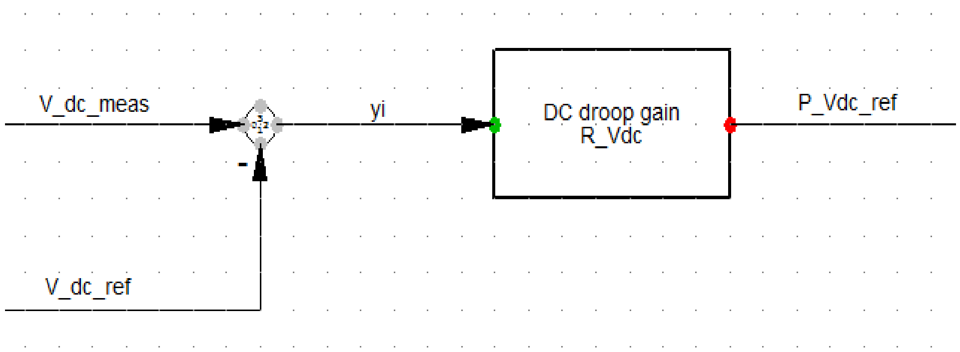

Figure 3 DC voltage droop controller

2.3.3. Frequency droop controller

The frequency droop controller resembles the primary frequency response of the conventional power plants. A proportional control action is applied to the frequency error, in order to adjust the power flow from the converter to the connected AC system according to the grid frequency deviation. The block diagram of the frequency droop controller is reported in Figure 4.

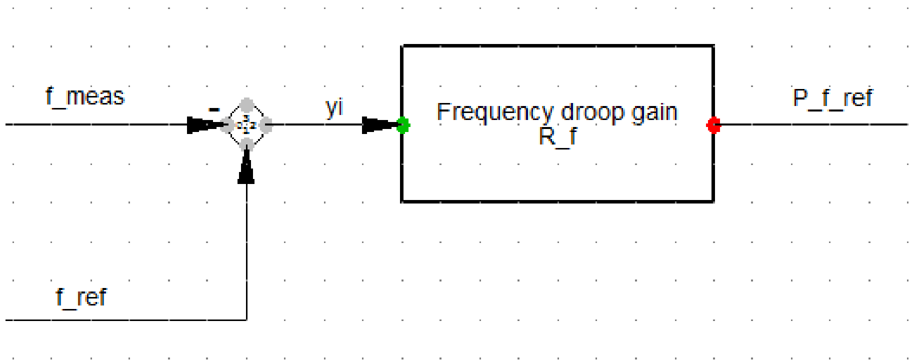

Figure 4 Frequency droop controller

2.3.4. AC voltage droop controller

The AC voltage droop controller is added to the control model as a support system to the reactive power control. Through this controller, the converter is able to respond to AC voltage magnitude variations and adapt its reactive power injection/absorption accordingly. The model is similar to the other droop control functions presented above and is illustrated in Figure 5.

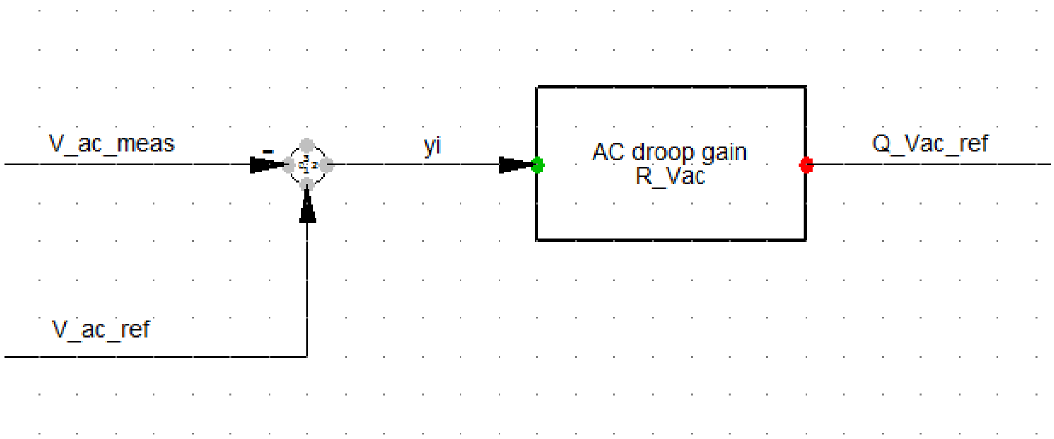

Figure 5 AC voltage droop controller

2.3.5. DC overvoltage controller

The DC overvoltage controller is added to the control model for limiting the DC voltage within a certain range. Therefore, drifts of the DC voltage, which are not automatically prevented by the DC voltage droop controller, are avoided. The DC voltage limiter detects the DC voltage; if this exceeds the overvoltage threshold, the controller provides signal to the power control block for adjusting the power output of the converter. The block diagram of the DC overvoltage controller is presented in Figure 6.

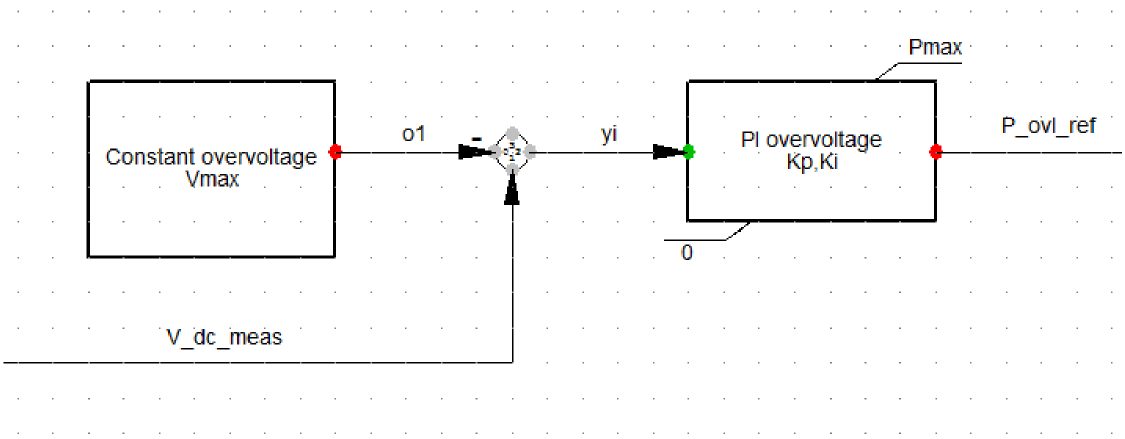

Figure 6 DC overvoltage controller

2.3.6. Measurement blocks

In Figure 1 of the control system a set of measurement blocks is presented, consisting of the following measurement devices:

- Phased locked loop (PLL), to measure the phase angle and frequency.
- AC voltage measurement device, to sense the AC voltage at the point of connection of the converter.
- Power measurement device, to measure the active and reactive power flows from/to the converter. Positive measurements denote load orientation of the power flow.
- DC voltage measurement device, to measure the DC voltage value.
- AC current measurement device, to measure the AC current flowing in the converter's AC phases. This device is not presented in Figure 1 of the control system, since it is implemented internally in the current control of the converter.

The measurement devices are built by the standard models provided by PowerFactory. However, the DC voltage measurement device has undergone a modification, since the DC voltage measurement must be taken on both terminals and modified to provide the right p.u. value, as shown in Figure 7. It should be mentioned that such a modification can only be applied in symmetrical DC links.

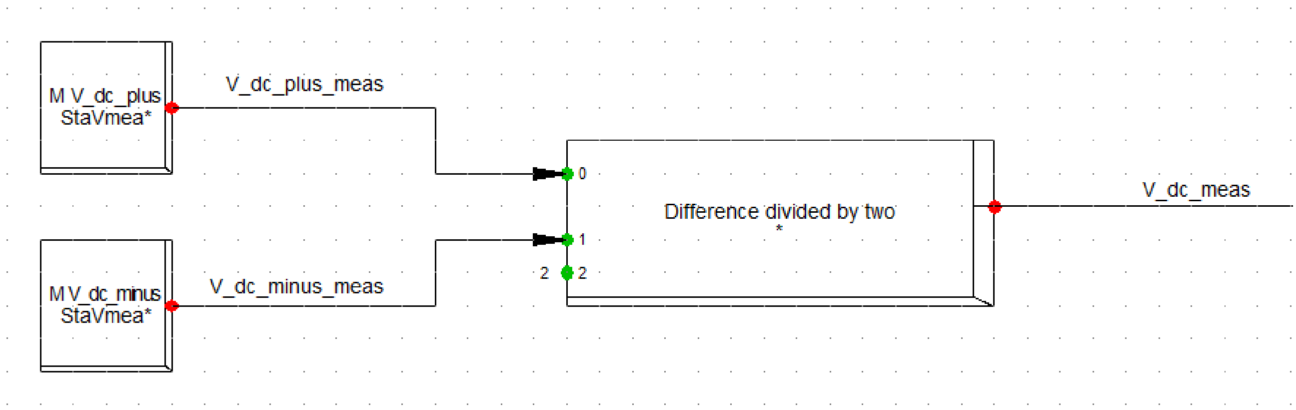

Figure 7 Modification of DC voltage measurement

3. Simulation events and results

In this section four simulated events are presented. These events are performed to investigate the performance of the converter controllers. The events occur in steps with duration of 1 sec. After the first milliseconds from the beginning of the event, the system should be stabilised in a new equilibrium point. With the end of the event the system returns to its previous conditions.

3.1. Step change in the reactive power consumption of one AC grid

The aim of this event is to test the functionality of the AC voltage droop controller. The reactive power in an AC grid is changed and the AC droop controller should detect the consequent change in the AC voltage and change the converter's reactive power output according to the droop constant. Specifically in this event, the reactive power consumption of the Holland AC grid is decreased stepwise. As a result, the AC voltage drops, as it can be observed in the upper part of Figure 8. The AC voltage droop controller detects the change of the AC voltage from its reference value and gives an order for an increase in the reactive power output of the converter, as it is shown in the lower part of Figure 8.

The same conclusions can be drawn in the case of the Germany grid, as presented in Figure 8. This occurs due to the connection of the two systems through AC overhead lines; the disturbance in one grid affects also the other. Therefore, the AC voltage at the Germany busbar drops and, thus, the controller of the corresponding converter gives signal for more reactive power. On the contrary, the AC voltage of the England grid remains unaffected, since it is connected with the two other networks only through DC lines. The relevant converter prevents the cascade of the disturbance, by keeping the AC voltage to its reference value through its controller.

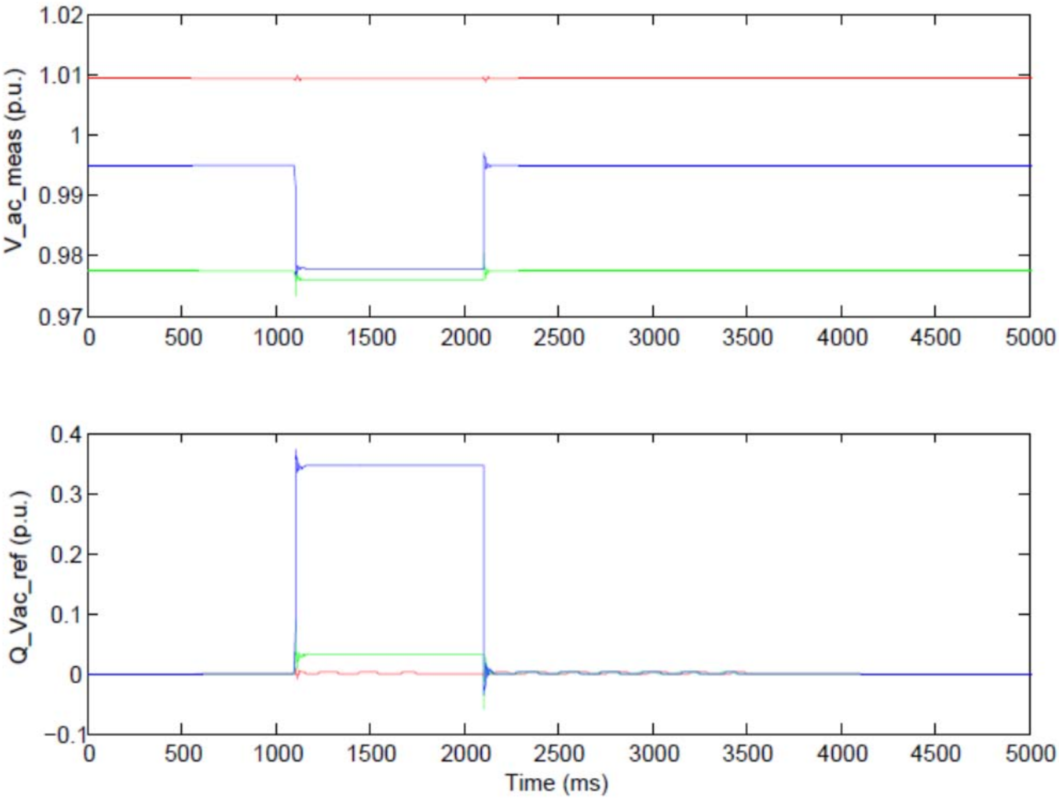

Figure 8 Performance of the AC voltage droop controller
Red: England grid, Green: Germany grid, Blue: Holland grid

3.2. Step change in the active power consumption of one AC grid

The purpose of this event is to examine the performance of the AC frequency droop controller. The active power in one grid changes and therefore the grid frequency also changes. The frequency droop controller should monitor this frequency deviation and should adjust the active power output of the converter according to the frequency droop factor. In this event, an increase in active power consumption occurs in the England grid, leading to a decrease in the frequency of this network, as illustrated in the upper part of Figure 9. The frequency droop controller detects the change in frequency and order higher active power injection from the converter to the grid, as presented in the lower part of Figure 9. The frequency in the other two networks remains unchanged, as the England grid is connected with them only through DC links. The converters of the relevant DC transmission systems control the frequency of the networks, keeping it in its reference value. The oscillations in the signals of the other two systems can be explained by the instantaneous change in the active power flow in the DC links, until the converter connected to the England system adjusts its output. After the first second from the disturbance, the England converter provides the required active power by itself, without any change in the active power outputs of the other converters.

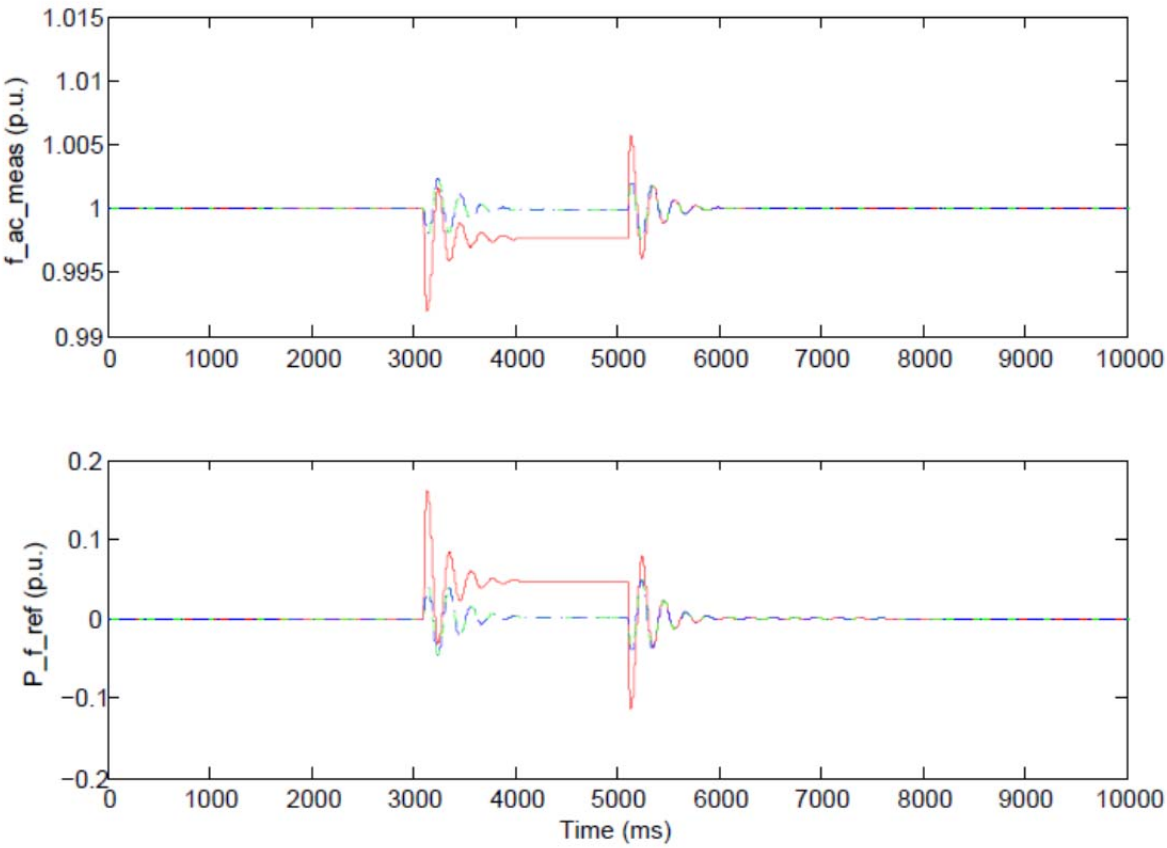

Figure 9 Performance of AC frequency droop controller
Red: England grid, Green: Germany grid, Blue: Holland grid

3.3. Step change in the reference value of the active power output of one converter

The scope of this test is to identify the performance of the DC voltage droop controller. This control system should monitor changes in the DC voltage due to power imbalances in the DC lines and adjust the active power output of the converters, in order to restore the power balance. In the simulated event, the reference power value of the England converter is decreased. As a result, the converter provides less power to the England grid than initially, which leads to an increase in the DC voltage of the England DC bus, as shown in the upper part of Figure 10. The DC voltage is a universal indicator for the DC grid. Therefore, it increases in all DC buses in the same manner, as it can be observed from Figure 10. The deviation of the DC voltage from its reference value activates the DC voltage droop controllers, which give the order to the converters to increase their outputs, as illustrated in the lower part of Figure 10. This means that the England converter is forced to increase the injection to England grid, which has been reduced due to the change in the reference value. Simultaneously, the other two converters are forced to increase their injections to the corresponding grids, i.e. to reduce the amount of power that absorb from the connected systems, as shown in Figure 11. In this way, the power excess in the DC links is diminished and the power balance in the DC grid is restored. Therefore, the DC voltage is stabilised and a new equilibrium point is established.

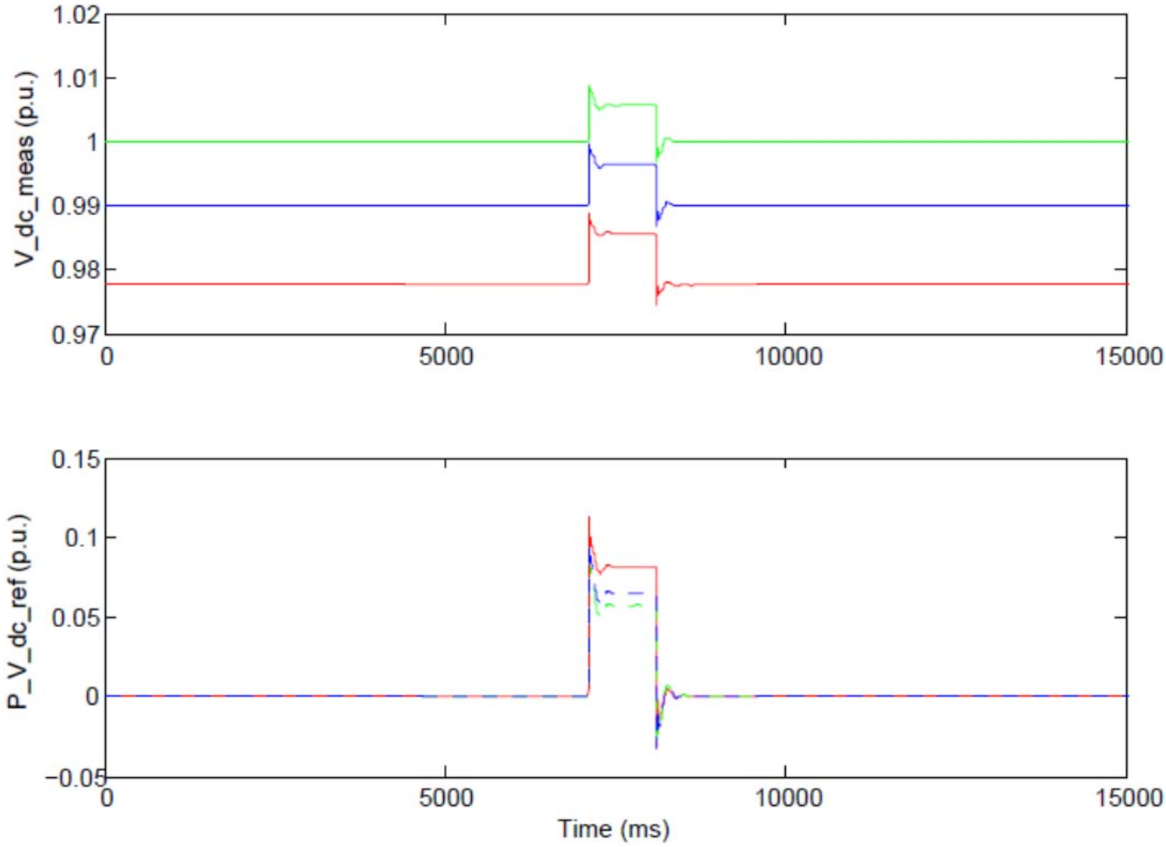

Figure 10 Performance of DC voltage droop controller
Red: England grid, Green: Germany grid, Blue: Holland grid

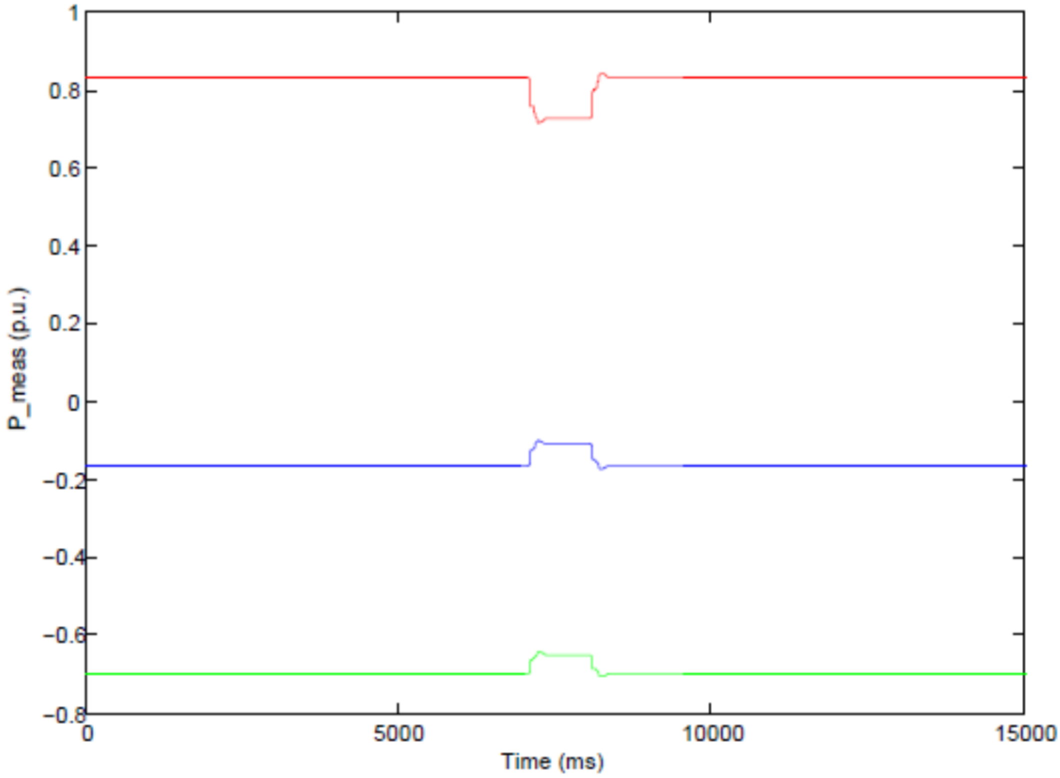

Figure 11 Effect of DC voltage droop controller
Red: England grid, Green: Germany grid, Blue: Holland grid

3.4. Converter trip

This event is performed to investigate the function of the DC overvoltage limiter. In a severe fault or trip of equipment, the power balance in the DC grid could be lost, leading to significant increase in the DC voltage. However, the DC overvoltage should not exceed specific limits. Therefore, an additional signal should be provided to the converter to adjust its power output. During the event that simulated in this work, the England converter is tripped and thus it does not provide active power to the connected system. Consequently, the DC voltage is significantly increased exactly after the beginning of the event, as illustrated in Figure 12. As a result, the DC overvoltage limiters of the other two converters give command to reduce their injection to the DC grid. For restoring the power balance in the DC grid, the Holland converter stops injecting power into the DC grid and starts injecting power to the connected AC system (power inverse), as shown in Figure 13. The power injected to Holland AC grid comes from the Germany system. The Germany converter continues to inject power to the DC grid, but in a lower level than initially. However, the DC voltage remains in a very high value, above the overvoltage limit, as presented in the upper part of Figure 12. Hence, the DC overvoltage limiter of the Germany converter (the only one which injects power to the DC grid) remains activated, in order to force the converter to provide more power into the connected AC system, i.e. less power to the DC grid (the negative sign denotes the DC grid oriented power flow).

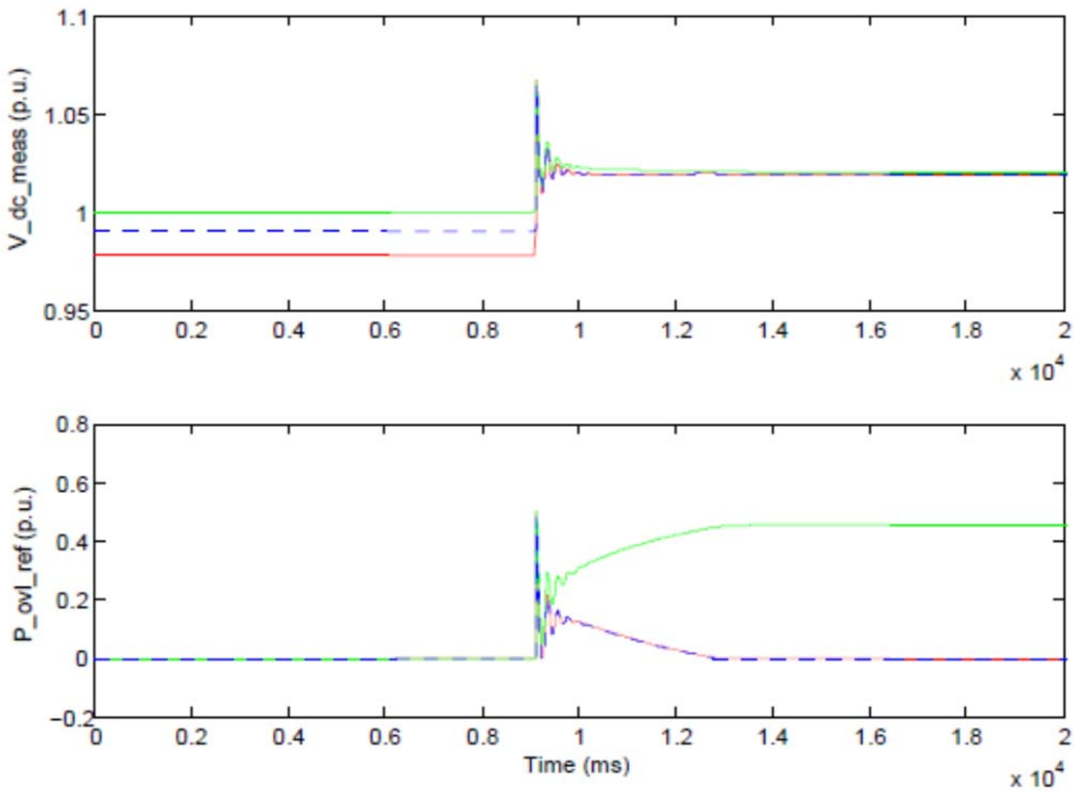

Figure 12 Performance of DC overvoltage limiter
Red: England grid, Green: Germany grid, Blue: Holland grid

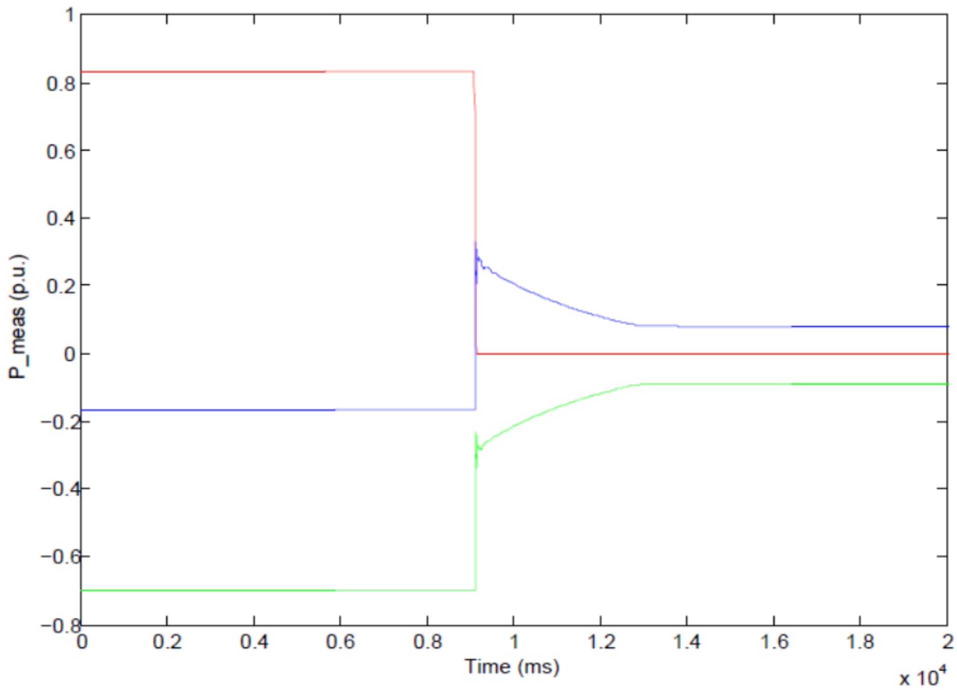

Figure 13 Effect of DC overvoltage limiter
Red: England grid, Green: Germany grid, Blue: Holland

4. Future work

A number of significant aspects should be taken into consideration and included in future implementations, for improving the performance of the models. These are not limited to:

- A limitation should be introduced on the current references.
- The parameters of the PI controllers in overvoltage limiter and current control should be improved to optimise the performance of the converter.
- A fault ride through controller can be implemented in compliance with grid codes.
- Secondary controllers can also be incorporated in the model, acting on the reference signals for the correct realisation of scheduled power flow in the connected systems.
- The control system may need additional modifiacation in order to be able to connect offshore wind farms. The developed converter model is assumed to be connected to relatively strong AC grids. However, when the converter is connected to offshore wind farms, it may actually be required to set voltage magnitude and angle.

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Appendix: Grid layout